

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From - To) 09/01/2000 - 08/31/2003
4. TITLE AND SUBTITLE Ultracold Atom Optics Science and Technology		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER DAAD19-00-1-0460		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Sarah Thompson Dana Anderson		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Colorado - Boulder 440 UCB Boulder, CO 80309		8. PERFORMING ORGANIZATION REPORT NUMBER 41547.1-EL-MUR		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT In past experiments we had focused on the formation of a molecular condensate close to a Feshbach Resonance in a 85 Rb atomic condensate by performing "Ramsey type" experiments. By applying two rapid magnetic field pulses toward the Feshbach resonance which were separated by a variable "evolution time" we were able to observe interference fringes between the atomic and molecular states. The damping rate of the interference fringes has since been measured; it confirms the coherent nature of the molecular state and also provides information about mean field interactions between and within the molecular and atomic condensates. More efficient production of molecules is predicted by adiabatically increasing (rather than pulsing) the magnetic field through the Feshbach resonance from below. In our most recent experiments we have observed a significant loss of atoms from both a thermal cloud and atomic condensate after ramping the field sufficiently slowly through this resonance. This loss is partially reversed by decreasing the field back down through the resonance again to a region where the molecular state is no longer bound. These two observations provide strong evidence that molecules are being formed by this method. Future research will include direct absorption imaging of the molecules and investigation of molecular decay mechanisms.				
15. SUBJECT TERMS Feshbach, Ultracold Atoms				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU	3
			19a. NAME OF RESPONSIBLE PERSON	
			19b. TELEPHONE NUMBER (include area code)	

This Multidisciplinary University Research Initiative on ultra cold atom optics science and technology has three focus areas. One entails the study and development of ultra cold atom sources; another entails the development of atom optical waveguides, and the other the development of electromagnetically induced transparency (EIT) technology. The efforts involve close interaction between theoretical and experimental research. The Bose-Einstein Condensate, or BEC, is the atomic analog of the laser. It therefore expected to play a pivotal role in the development of applied atom optical systems such as inertial sensors and other systems that capitalize on the coherent properties of an atomic source. At present Bose-Einstein condensation has been demonstrated in merely a small handful of atomic species, and such sources have been produced with a very restricted set of experimental techniques.

In recent work, this MURI research effort explored the dynamics of a “programmable” BEC. The formation of a BEC depends critically on the interaction dynamics of the atomic species. MURI researchers tuned the interaction using an externally applied magnetic field. Of particular interest is the nature of the dynamics as the interaction is tuned from repulsive to attractive. As the sign of the interaction is changed, so the cloud of atoms undergoes a violent collapse and subsequent explosion. The investigation of the detailed dynamics has revealed aspects that challenge current theoretical models. Such studies are destined to lead to better theoretical models of BEC and subsequently, to a wider spectrum of BEC sources. Unlike the photon, ultra cold atomic systems can be group into two species: Bose gasses and Fermi gasses, depending on the total atomic spin. The majority of research around the world focuses on Bose systems. However, a Fermi gas offers some extremely useful characteristics for applications, and therefore a portion of the MURI work looks at the properties of Fermi gas systems. MURI research has investigated high critical temperature super-fluidity in Quantum degenerate Fermi gasses—a phenomenon that finds its analog in the Bardeen-Cooper-Schrieffer (BCS) theory, describing superconductivity in metals.

The research has lead to the experimental possibility of studying the transition regime where there is a crossover from the BCS phase of weakly-coupled fermions to the BEC. Much of the application focus of ultra cold atom optics relies on the development of atom waveguide technology—a technology that does for atoms what optical waveguides have done for light. To this end this interim research period saw the completion of a catalog of atom waveguide devices. The MURI group had already demonstrated atom waveguides before the commencement of the MURI funding period. Subsequent experiments demonstrated an atom beam splitter—a key component of waveguide technology. The end of 2000 saw the completion of magnetic switch for integrated atom optics. Using magnetic fields generated by lithographed current-carrying wires, researchers we able to switch guided cold atoms from one waveguide to another on a single substrate. The switch concept was implemented in a general way that can be applied to atomic waveguide systems of almost arbitrary complexity.

Current work in atom waveguides has now made a turn to develop an efficient BEC source for coupling a BEC into an atom waveguide. After completion of the source a key step is to demonstrate guided atom interferometry with a simple waveguide structure. Relatively little is understood about the nature of atoms guided by magnetic fields—the technology is certainly much behind and more complex than the optical guided-wave analogs. Thus, the MURI effort has placed some emphasis in processes that are expected to be deleterious to waveguide device

performance. In particular, an investigation of the propagation of atoms in a waveguide having bends has provided a better understanding of the nature of atom heating that can occur. So far these studies have modeled the waveguide systems already demonstrated wherein the atoms propagate classically in the waveguide. Future work will consider the quantum mechanical motion of a BEC where one is particularly concerned with decoherence of the guided cloud of atoms. Recent work on the nonlinear optical phenomena of Electromagnetically-induced transparency, or EIT, has led to a new domain of both nonlinear optics and atomic physics. Cold-atom EIT has led to experiments in which light made to propagate slowly and then is literally stopped in a cloud of atoms. These experiments have revealed enormous potential for optically-controlled signal processing using the properties of an ultra cold gas. Furthermore, MURI research on EIT has shown that one can in turn use EIT to explore a new class of techniques for manipulating atomic systems. Indeed, EIT forces can be large, and they can be very specifically tuned to obtain a given atomic mechanical response. Such forces may lead to new techniques in generating and controlling ultra cold gasses.

Ms. Thompson's experimental research studies have focused on Feshbach resonances in atomic rubidium. The use of Feshbach resonances allows one to tune the interaction among ultra-cold atoms. For example, atomic collisions are described by a *scattering length*. A positive scattering length means that two atoms on a collision course will be repelled from each other while a negative scattering length indicates they will be attracted. In particular the nature of atomic Bose condensation is dramatically different for positive versus negative scattering lengths. Remarkably, the Feshbach resonance can be used to tune the interaction length from positive to negative, and to adjust its magnitude as well. Such tuning allows one to use a single atomic species to study a variety of effects that would normally be done with a corresponding variety of atoms.

Atoms have a negative scattering length tend to form molecules. Feshbach resonances open an avenue to *molecular* BEC. This is the subject of a recent paper by Ms. Thompson and collaborators appearing in Nature ("Atom-molecule coherence in a Bose-Einstein condensate", E.A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, Nature, **417**, p529 (May, 2002). Molecular BEC remains among the very challenging and sought-after domains for ultra cold science.

In past experiments we had focused on the formation of a molecular condensate close to a Feshbach resonance in a 85Rb atomic condensate by performing "Ramsey type" experiments. By applying two rapid magnetic field pulses toward the Feshbach resonance which were separated by a variable "evolution time" we were able to observe interference fringes between the atomic and molecular states. The damping rate of the interference fringes has since been measured; it confirms the coherent nature of the molecular state and also provides information about mean field interactions between and within the molecular and atomic condensates.

More efficient production of molecules is predicted by adiabatically increasing (rather than pulsing) the magnetic field through the Feshbach resonance from below. In our most recent experiments we have observed a significant loss of atoms from both a thermal cloud and atomic condensate after ramping the field sufficiently slowly through this resonance. This loss is partially reversed by decreasing the field back down through the resonance again to a region

where the molecular state is no longer bound. These two observations provide strong evidence that molecules are being formed by this method. Future research will include direct absorption imaging of the molecules and investigation of molecular decay mechanisms.

Publications:

N. Blanchard and A. Zozulya, "Transverse heating due to nonadiabatic propagation of cold atoms in an atomic guide," *Opt. Comm.* Vol. 190/1-6, pp. 231--237 (2001).

Elizabeth A. Donley, Neil R. Claussen, Simon L. Cornish, Jacob L. Roberts, Eric A. Cornell and Carl E. Wieman, "Dynamics of collapsing and exploding Bose-Einstein condensates," *Nature* (submitted).

S. E. Harris, "Pondermotive Forces with Slow Light," *Phys Rev. Lett.* 85, 4032-4035 (November 2000).

S. E. Harris, A. V. Sokolov, D. R. Walker, D. D. Yavuz, and G. Y. Yin, "Collinear Light Scattering Using Electromagnetically Induced Transparency," in *Atomic Physics 17*, edited by E. Arimondo, P. DeNatale, and M. Inguscio (American Institute of Physics, New York, 2001), pp. 189-203.

M. Holland, S.J.J.M.F. Kokkelmans, M.L. Chiofalo, and R. Walser, "Resonance superfluidity in a quantum degenerate Fermi gas," *Phys. Rev. Lett.* (submitted)

D. Muller, E. A. Cornell, M. Prevedelli, P. D. D. Schwindt, A. Zozulya and D. Z. Anderson, "Waveguide atom beamsplitter for laser-cooled neutral atoms," *Opt. Lett.* 25, 1382-1384 (2000)

D. Muller, E. A. Cornell, M. Prevedelli, P. D. D. Schwindt, Y.-J. Wang and D. Z. Anderson, "A magnetic switch for integrated atom optics," *Phys. Rev. A* 63, 041602(R)/1-3 (2001)

A.V. Sokolov, S.J. Sharpe, M. Shverdin, D.R. Walker, D.D. Yavuz, G.Y. Yin, and S.E. Harris, "Optical Frequency Conversion by a Rotating Molecular Waveplate," *Optic Letters*, (submitted).

E.A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, "Atom-molecule coherence in a Bose-Einstein condensate", *Nature*, **417**, p529 (May, 2002)